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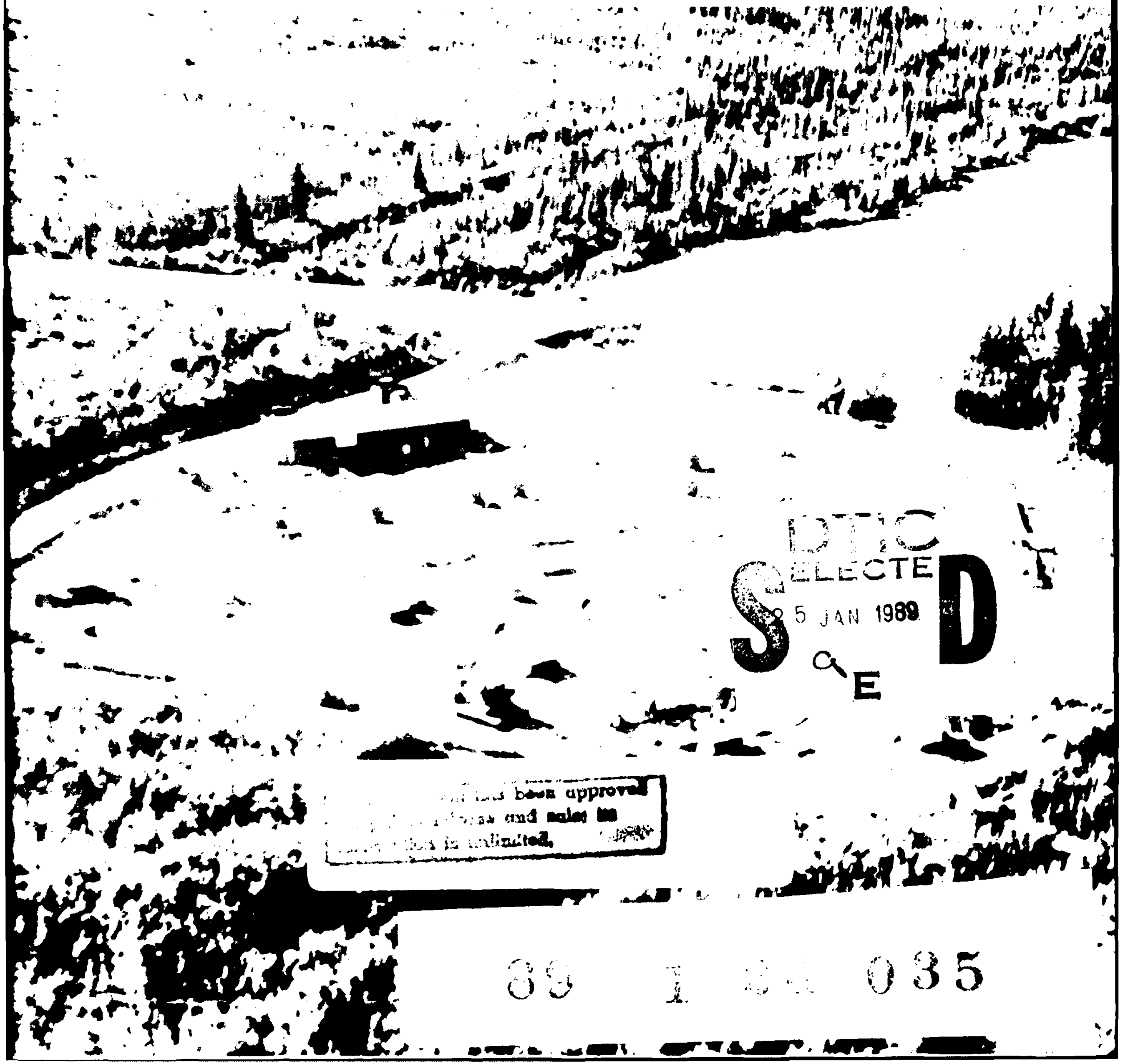
nfrozen water contents of undisturbed nd remolded Alaskan silt as determined y nuclear magnetic resonance



For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Air photo of Chilled Gas Test Facility, operated by the Northwest Alaska Pipeline Company in Fairbanks, Alaska. (Photo by F. Crory.)

CRREL Report 88-19

November 1988

Unfrozen water contents of undisturbed and remolded Alaskan silt as determined by nuclear magnetic resonance

Allen R. Tice, Patrick B. Black and Richard L. Berg

Prepared for
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Unfrozen water content as a function of temperature was measured in the laboratory using nuclear magnetic resonance (NMR) for 16 undisturbed frozen cores acquired from the Northwest Alaska Pipeline Company Chilled Gas Test Facility. The cores were then remolded and brought to their original densities and water contents, and unfrozen water content as a function of temperature was again measured over three warming and cooling cycles. It was found that differences in unfrozen water contents between the undisturbed warming and cooling curves depended upon relative degree of saturation and its effect on soil structure. Only slight changes occurred during the three warming curves of the remolded soil, indicating minor freezing and thawing consequences on the soil structure.

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PREFACE

This report was prepared by Allen R. Tice, Physical Science Technician, and Dr. Patrick B. Black, Research Physical Scientist, of the Geochemical Sciences Branch, Research Division, and by Dr. Richard L. Berg, Research Civil Engineer, of the Civil and Geotechnical Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this project was provided by the Northwest Alaska Pipeline Company and DA Project 4A161102 AT24, *Research in Snow, Ice and Frozen Ground*, Scientific Area A, *Properties of Cold Regions Materials*, Work Unit 002, *Properties of Frozen Soils.*

Timothy Pangburn of CRREL and Dr. H.M. Selim of Louisiana State University technically reviewed this report.

Unfrozen Water Contents of Undisturbed and Remolded Alaskan Silt as Determined by Nuclear Magnetic Resonance

ALLEN R. TICE, PATRICK B. BLACK AND RICHARD L. BERG

INTRODUCTION

The technical difficulties encountered during the construction of the trans-Alaska pipeline demonstrate the need for knowing the physical properties of soil when designing for engineering applications in cold regions. Uncertainty regarding the unusual behavior of the thermomechanical properties of frozen soil made the design process for the pipeline long and expensive. This lack of understanding primarily results from the unique heat and mass transfer properties of frozen soil that require detailed knowledge of the soil's constitutive relationships.

It has been recognized since the pioneering work of Taber (1930) and Beskow (1935) that the existence of a continuous liquid layer separating the soil matrix from the ice in frozen soil is the controlling factor in the dynamics of soil freezing. All constitutive relationships for thermal, hydraulic and mechanical properties of frozen soil are functions of the quantity of unfrozen water present (Black and Miller 1985). Successful engineering solutions to cold climate construction problems, such as thermopile design for pipeline support and long-term water migration towards cold pipelines, therefore depend upon ability to predict or measure the amount of unfrozen water present.

The amount of unfrozen water present in frozen soil is dependent upon the physical, chemical and mineralogical composition of the soil. Anderson and Tice (1973) found the dominant factors to be specific surface area, solute concentration, temperature, confining pressure and, to a lesser extent, initial water content and surface chemistry of the soil matrix. The present lack of understanding of the complex interactions between these factors prohibits the development of predictive models of unfrozen water content based upon all of them. It is because of this limitation that methods to measure unfrozen water content directly or indirectly are employed.

In this study we measured the unfrozen water content change due to a temperature change for 16 undisturbed soil samples by employing NMR (nuclear magnetic resonance). These data are perhaps the only public domain measurements of unfrozen water contents on undisturbed frozen samples (the undisturbed samples of Pusch [1979] and Tice et al. [1981] were initially unfrozen). As such, they contain all in-situ factors that affect unfrozen water content and perhaps represent the first test of the ability of NMR to determine in-situ unfrozen water contents.

EXPERIMENT

The soils investigated were taken from the Northwest Alaska Pipeline Company (NAPLINE) Chilled Gas Test Facility near Fairbanks, Alaska. The cores were recovered by NAPLINE during their 1979 drilling program. Each frozen core was marked with a project number, boring number and sample number. We were not furnished with a drawing showing bore hole locations, but for the purpose of this work, location is unimportant.

Sixteen frozen cores packed in dry ice were received at CRREL in mid-January 1980. They were removed from the shipping container and allowed to equilibrate at a temperature of -3°C for two days to avoid brittle fracture during sample preparation. A frozen specimen was extracted from the center axis of each core by hydraulically pressing a thin-walled stainless steel core barrel into the larger core and its volume measured. Soil texture data for each specimen are given in Table 1. The soil type for all specimens is ML (a silt-clay).

The specimens were removed from the barrel and drilled with a 0.5-mm-diam bit to make a hole 2 cm deep. A copper-constantan thermocouple was inserted in the hole to monitor temperature changes of the sample throughout the experiments. The specimens were then placed in 1.68-cm-inside-

Table 1. Sieve and hydrometer analysis of NAPLINE soil.

Project/ Sample/ Boring	*% silt-clay*	*% < 0.002 m*	*D10*	*D30*	*D60*
802/2/1	*	*	*	*	*
802/3/1	98.9	49.1	0.004	0.012	0.026
802/3/2	98.5	26.0	0.008	0.022	0.038
802/3/3	99.2	45.3	0.006	0.014	0.025
802/13/2	91.5	30.9	0.005	0.020	0.035
802/13/3	99.3	59.0	0.001	0.008	0.02
802/16/4	96.1	34.2	0.006	0.018	0.034
802/18/4	98.1	42.5	0.001	0.013	0.03
852802/4/2	97.8	45.1	0.005	0.013	0.029
852802/6/1	99.0	36.8	0.008	0.017	0.03
941201/1	94.2	30.8	0.003	0.020	0.035
941201/2	98.6	68.7	0.001	0.004	0.015
941201/3	99.4	68.5	0.001	0.004	0.017
941201/4	99.4	53.1	0.002	0.010	0.023
941201/5	98.9	51.5	0.004	0.012	0.024
941201/6	99.1	54.2	0.001	0.009	0.023

* No data.

diam test tubes and sealed with rubber stoppers to prevent moisture losses. Following specimen preparation, all test tubes were placed in a constant temperature bath containing an ethylene glycol and water mixture and allowed to equilibrate at -25°C overnight.

A Praxis PR-103 pulsed nuclear magnetic resonance analyzer, factory-tuned to detect only hydrogen, was used to determine unfrozen water contents. Each test specimen was removed sequentially from the bath, wiped dry and inserted in the NMR probe. After the four seconds required to record specimen temperature and first-pulse NMR signal amplitude, the specimen was reinserted in the bath. When all observations had been completed at a given temperature, the bath temperature was increased by 3°C. Thermal equilibrium was attained after approximately 45 minutes and measurements repeated.

When -10°C was reached, the bath temperature was increased by smaller increments until -1.5°C was reached. Then an even smaller temperature increment was employed until all soil water was thawed.

Following the warming run, the test samples were quickly refrozen and brought to a temperature slightly below 0°C. Cooling observations were made in a manner similar to those made during warming and stopped when the specimens reached a temperature of -25°C. Water contents were then determined gravimetrically and are presented in Table 2 along with dry bulk densities, volumetric water contents, porosities and relative degrees of saturation based upon the initial volumes of the extracted specimens.

After completing the water content determinations, we rewetted each oven-dry specimen to approximate its original water content with distilled water, sealed it and allowed it to set for several days for moisture equilibration. Each specimen was then thoroughly remixed and compacted to its original density in carefully calibrated glass tubes. The sealed tubes were then quickly frozen to -25°C with no attempt to de-air the soil or water.

Three individual warming cycles were conducted for all except two remolded specimens. These two were not used because of ethylene glycol contamination from the constant temperature bath. After the last warming cycle, each specimen was again oven-dried and its gravimetric water content determined.

The unfrozen water contents at each temperature were determined from the measured first pulse NMR amplitude. The technique is described by Tice et al. (1978, 1981, 1982). Briefly, the ratio of the gravimetric water content to the first pulse amplitude of the ice-free case for each test specimen was determined. Unfrozen water contents were then deduced by multiplying the measured first pulse amplitude at the different temperatures by the above determined ice-free ratio. The data are listed in Appendix A.

Table 2. Sample identification, water content and density for NAPLINE data.

Project/ Sample/ Boring	State*	Percent water		Bulk density		Porosity	Relative saturation
		Weight	Volume	Wet	Dry		
802/2/1	Undisturbed	45.35	57.53	1.66	1.14	0.58	0.99
	Remolded	45.16	—†	1.63	—	—	—
802/3/1	Undisturbed	49.22	59.99	1.64	1.10	0.60	1.01
	Remolded	49.33	—	1.62	—	—	—
802/3/2	Undisturbed	32.30	47.31	1.74	1.32	0.52	0.91
	Remolded	32.49	—	1.74	—	—	—
802/3/3	Undisturbed	48.78	60.06	1.65	1.11	0.58	1.03
	Remolded	48.63	—	1.63	—	—	—
802/13/2	Undisturbed	46.43	59.83	1.70	1.16	0.55	1.10
	Remolded	47.34	—	1.67	—	—	—
802/13/3	Undisturbed	30.94	47.18	1.80	1.37	0.49	0.97
	Remolded	32.23	—	1.65	—	—	—
802/16/4	Undisturbed	30.05	49.26	1.92	1.47	0.46	1.07
	Remolded	30.65	—	1.92	—	—	—
802/18/4	Undisturbed	56.66	64.68	1.61	1.03	0.62	1.04
	Remolded	58.84	—	1.66	—	—	—
852802/4/2	Undisturbed	41.44	56.66	1.74	1.23	0.54	1.05
	Remolded	41.63	—	1.69	—	—	—
852802/6/1	Undisturbed	49.67	59.08	1.60	1.07	0.60	0.98
941201/1/-	Undisturbed	31.64	48.84	1.83	1.40	0.51	0.96
	Remolded	31.59	—	1.86	—	—	—
941201/2/-	Undisturbed	40.32	54.73	1.71	1.22	0.55	1.00
	Remolded	40.44	—	1.73	—	—	—
941201/3/-	Undisturbed	63.67	65.84	1.52	0.93	0.65	1.02
	Remolded	65.52	—	1.57	—	—	—
941201/4/-	Undisturbed	47.92	—	—	—	—	—
	Remolded	47.88	—	1.66	—	—	—
941201/5/-	Undisturbed	67.31	67.73	1.52	0.9	0.66	1.03
941201/6/-	Undisturbed	44.95	57.70	1.67	1.1	0.57	1.02
	Remolded	45.94	—	1.64	—	—	—

* U—undisturbed, R—remolded.
† No data.

RESULTS AND DISCUSSION

Anderson and Tice (1973) reported that unfrozen water content of a soil as a function of temperature could be represented in the following form:

$$W_u = \alpha\theta^{\beta} \qquad (1)$$

where W_u (mass water/mass soil) is unfrozen water content in percentage of dry sample weight, θ is the temperature (in degrees Celsius) below 0°C expressed as a positive number and α and β are regression constants characteristic of each soil.

The logarithms of data in Appendix A were linearly regressed to eq 1 and optimal values of α and β determined. Resulting values along with r^2 values for the analysis are presented in Table 3. Figure 1 contains the best fit curves as predicted from eq 1 using values of α and β from Table 3, excluding data points for two sets of specimens, both undisturbed and remolded.

All undisturbed specimens exhibited hysteresis between warming and cooling curves. They differ only in amount and timing of hysteresis. It is important to note that the difference in amount of unfrozen water between the warming and cooling

Table 3. Least-squares regression coefficients of NAPLINE data to power curve.

Project/ Sample/ Boring	*Test conditions*	α	β	r^2
802/2/1	Undisturbed, warming	8.015	-0.456	0.908
	Undisturbed, cooling	7.403	-0.343	0.977
	Remolded, 1st warming	10.160	-0.711	0.728
	Remolded, 2nd warming	8.386	-0.619	0.789
	Remolded, 3rd warming	8.468	-0.577	0.855
802/3/1	Undisturbed, warming	8.319	-0.454	0.926
	Undisturbed, cooling	7.196	-0.288	0.950
	Remolded, 1st warming	8.915	-0.688	0.732
	Remolded, 2nd warming	7.579	-0.648	0.758
	Remolded, 3rd warming	7.792	-0.641	0.879
802/3/2	Undisturbed, warming	2.622	-0.559	0.910
	Undisturbed, cooling	1.866	-0.418	0.654
	Remolded, 1st warming	3.582	-0.725	0.541
	Remolded, 2nd warming	2.499	-0.793	0.817
	Remolded, 3rd warming	2.600	-0.749	0.708
802/3/3	Undisturbed, warming	7.663	-0.497	0.906
	Undisturbed, cooling	7.062	-0.327	0.980
	Remolded, 1st warming	7.146	-0.649	0.812
	Remolded, 2nd warming	7.146	-0.649	0.812
	Remolded, 3rd warming	7.471	-0.613	0.810
802/13/2	Undisturbed, warming	4.575	-0.599	0.860
	Undisturbed, cooling	4.695	-0.513	0.920
	Remolded, 1st warming	5.260	-0.657	0.893
	Remolded, 2nd warming	5.133	-0.591	0.984
	Remolded, 3rd warming	5.265	-0.746	0.951
802/13/3	Undisturbed, warming	5.866	-0.463	0.898
	Undisturbed, cooling	5.739	-0.372	0.974
	Remolded, 1st warming	7.418	-0.735	0.662
	Remolded, 2nd warming	6.176	-0.665	0.831
	Remolded, 3rd warming	6.163	-0.641	0.842
802/16/4	Undisturbed, warming	3.731	-0.352	0.891
	Undisturbed, cooling	3.800	-0.272	0.996
	Remolded, 1st warming	4.586	-0.597	0.639
	Remolded, 2nd warming	4.404	-0.537	0.735
	Remolded, 3rd warming	4.010	-0.442	0.923
802/18/4	Undisturbed, warming	4.259	-0.443	0.886
	Undisturbed, cooling	6.130	-0.367	0.988
	Remolded, 1st warming	5.502	-0.744	0.693
	Remolded, 2nd warming	7.085	-0.691	0.713
	Remolded, 3rd warming	6.191	-0.663	0.676
852802/4/2	Undisturbed, warming	5.781	-0.493	0.867
	Undisturbed, cooling	4.864	-0.353	0.988
	Remolded, 1st warming	6.757	-0.667	0.766
	Remolded, 2nd warming	6.231	-0.704	0.789
	Remolded, 3rd warming	6.110	-0.678	0.855
852802/6/1	Undisturbed, warming	7.144	-0.579	0.884
	Undisturbed, cooling	6.424	-0.571	0.958
941201/1	Undisturbed, warming	3.662	-0.584	0.836
	Undisturbed, cooling	2.614	-0.557	0.797
	Remolded, 1st warming	4.317	-0.629	0.904
	Remolded, 2nd warming	3.236	-0.885	0.730
	Remolded, 3rd warming	3.399	-1.040	0.919
941201/2	Undisturbed, warming	6.614	-0.444	0.851
	Undisturbed, cooling	5.681	-0.304	0.978
	Remolded, 1st warming	6.512	-0.657	0.923
	Remolded, 2nd warming	6.580	-0.698	0.871
	Remolded, 3rd warming	6.833	-0.694	0.799

Table 3 (cont'd).

Project/ Sample/ Boring	*Test conditions*	α	β	r^2
941201/3	Undisturbed, warming	5.365	-0.547	0.965
	Undisturbed, cooling	7.801	-0.454	0.994
	Remolded, 1st warming	6.115	-0.579	0.886
	Remolded, 2nd warming	7.883	-0.700	0.683
	Remolded, 3rd warming	7.916	-0.684	0.860
841201/4	Undisturbed, warming	5.244	-0.397	0.934
	Undisturbed, cooling	5.875	-0.306	0.951
	Remolded, 1st warming	6.104	-0.546	0.869
	Remolded, 2nd warming	6.408	-0.627	0.922
	Remolded, 3rd warming	6.749	-0.567	0.810
941201/5	Undisturbed, warming	7.554	-0.566	0.944
	Undisturbed, warming	9.113	-0.519	0.970
941201/6	Undisturbed, warming	7.893	-0.405	0.881
	Undisturbed, cooling	6.906	-0.311	0.983
	Remolded, 1st warming	6.174	-0.519	0.934
	Remolded, 2nd warming	6.945	-0.638	0.751
	Remolded, 3rd warming	6.871	-0.558	0.884
Pooled	Undisturbed, warming	5.574	-0.485	0.694
	Undisturbed, cooling	5.367	-0.383	0.523

curves at a given temperature is slight but some trends are noticeable. Close inspection reveals that the curves for specimens with the highest relative degree of saturation display more unfrozen water during cooling than warming for a given temperature (Fig. 1c). On the other hand, specimens with the lowest relative degree of saturation display less unfrozen water during cooling than warming for a given temperature. The remaining specimens, with relative degrees of saturation in between the extremes, display more unfrozen water during warming than cooling for the higher temperatures and then they display more unfrozen water during cooling than warming for the lower temperatures after the -1.5°C to -4°C temperature region (Fig. 1a).

If the hysteresis displayed in these data were merely a result of a Haines jump change in ice content, then the unfrozen water content during cooling would always be greater than warming for a given temperature for air-free frozen soil, just as the drying curve displays a larger water content than the wetting curve for the same suction in an ice-free soil characteristic curve (Koopmans and Miller 1966, Black and Tice, in prep.). Since all the specimens were close to or exceeded saturation, all the cooling curves should display more unfrozen water than the corresponding warming curve for a given temperature. But only the specimens with the highest relative degree of saturation consistently displayed the expected behavior.

While the degree of uncertainty of these data is unknown, we suspect that the uncertainties in determining the unfrozen water content and temperature are large enough that the expected behavior between respective warming and cooling curves cannot be clearly demonstrated. Therefore, the data that exhibit the expected behavior must have added influences that accentuate the amount of unfrozen water during cooling. This added influence to the hysteresis effect is attributed to a restructuring of the undisturbed frozen specimen upon thawing at the end of the warming run.

The soil used for these experiments is very similar to Fairbanks silt, and as such, is highly susceptible to frost heave (Berg and Johnson 1983). It seems reasonable, therefore, to suspect that ice lenses existed in the specimens and that specimens with the highest relative degree of saturation had the largest amount of segregated ice. Upon thawing of these lenses, soil settled into a more compact structure, which increased the bulk density and shifted the pore size distribution toward the smaller pores. The cooling curve of this different pore size distribution then reflected a greater fraction of smaller pores than the preceding warming curve with its original pore size distribution for a given temperature, ensuring an increased unfrozen water content. This process is the same as that explained by Taylor and Box (1961) for changes in the soil characteristic curve arising from changes in bulk density.

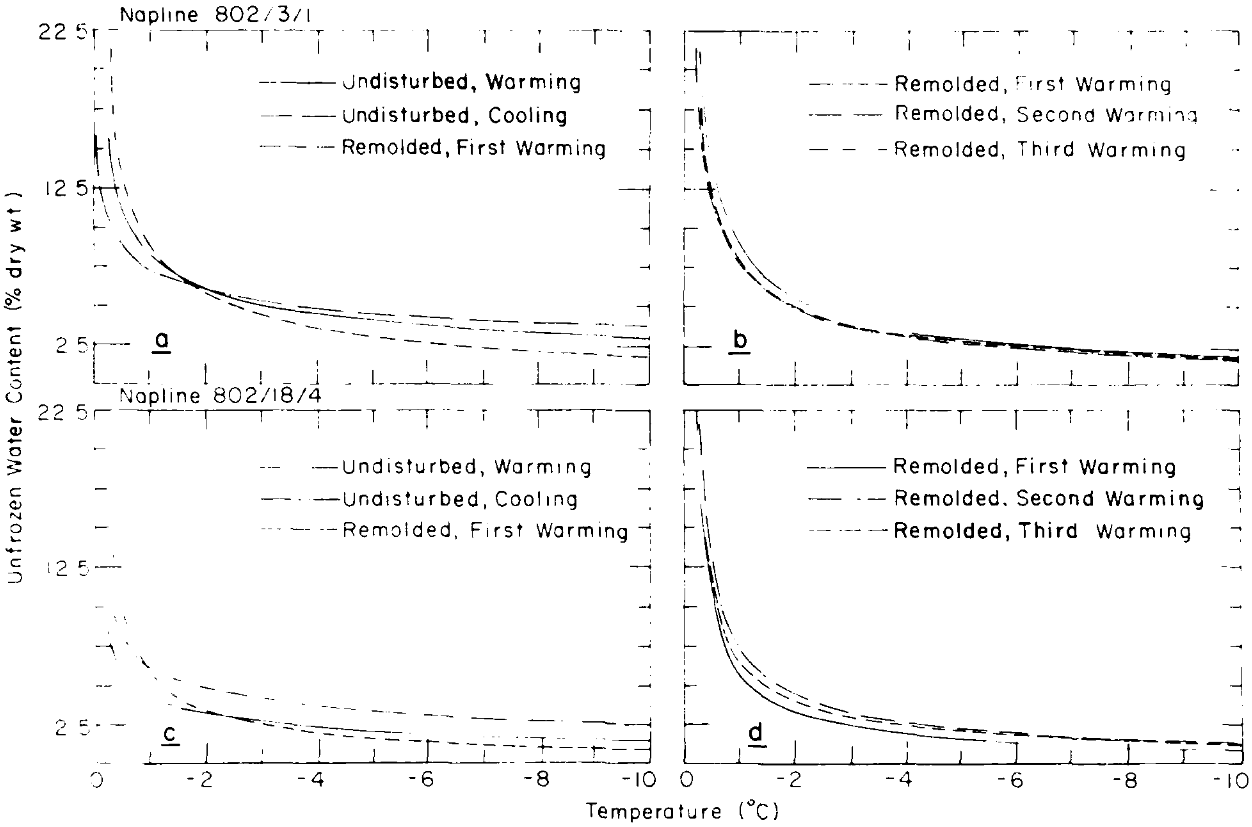


Figure 1. Unfrozen water contents vs temperature plots obtained from NMR analysis for two undisturbed and remolded NAPLINE soil samples.

a. NAPLINE 802/3/1 undisturbed warming and cooling and first remolded warming curves, no segregated water observed.

b. NAPLINE 802/3/1 remolded warming curves.

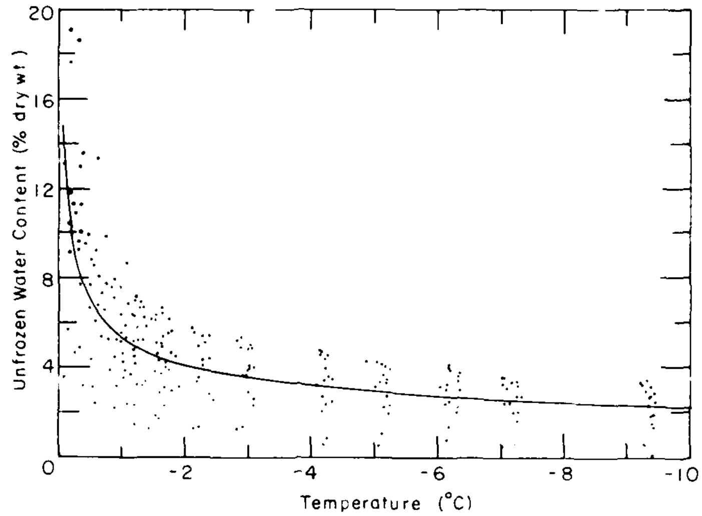
c. NAPLINE 802/18/4 undisturbed warming and cooling and first remolded warming curves, segregated water observed.

d. NAPLINE 802/18/4 remolded warming curves.

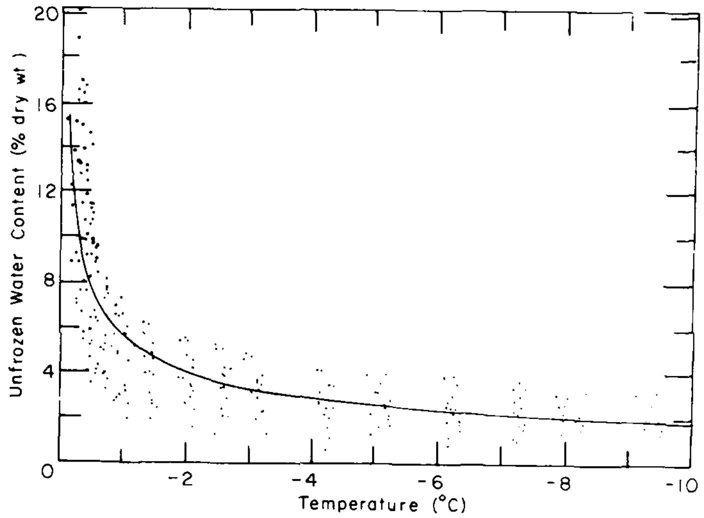
The first warming run of all remolded test samples contained more unfrozen water at the warm temperatures than either of the undisturbed curves and less unfrozen water at the cooler temperatures (Fig. 1a and 1c). Again this can be explained in terms of pore size distribution. A uniformly dense soil inevitably contains fewer large and small pores than an undisturbed, structured soil of same bulk density. Accordingly, the remolded sample contains more unfrozen water at the warmer temperatures because of a decreased number of large pores than present in the undisturbed soil.

The primary purpose of measuring three warming curves on the remolded soil was to determine changes in unfrozen water content arising from cyclic freezing and thawing cycles. If significant changes occurred, it would be reasonable to conclude that such cycles would cause mechanical strength changes in the soil. While all remolded warming curves show changes between the three curves (Fig. 1b and 1d), the changes are slight and display no consistent trend. The unfrozen water content does not always decrease with successive cycles and the relative degree of saturation does not appear to determine behavior. This observation is in agreement with data of Chamberlain and Gow (1979) who reported that structural changes induced by cyclically freezing and thawing silts were slight.

All undisturbed data for both warming and cooling cycles were pooled and fitted to eq 1; the results are given in Table 3. These data, along with best fit curves, are plotted in Figure 2. As expected, the r^2 values for these pooled data are much lower than those for individual undisturbed test samples but are not insignificant ($r^2 < 0.52$). Other relationships based upon soil physical characteristics were sought, but no distinctive behavior was observed. Since all specimens were from the same location and of the same soil type, such relationships would at best indicate uncertainties caused by the soils' inherent spatial variability.



a. Pooled undisturbed warming data and best fit curve.



b. Pooled undisturbed cooling data and best fit curve.

Figure 2. Unfrozen water contents vs temperature plots obtained from NMR analysis for 16 undisturbed frozen NAPLINE soil samples.

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APPENDIX A: SOIL FREEZING CURVE DATA

Undisturbed
Warming

(-°C)	(% dry wt.)
10.37	2.86
9.33	3.16
8.02	3.17
7.34	3.47
6.28	3.67
5.07	3.78
4.14	4.28
2.91	4.79
2.49	5.19
2.02	5.50
1.34	5.90
1.03	6.81
0.74	7.61
0.56	9.12
0.46	10.82
0.41	12.73
0.35	16.23
0.25	19.14

Undisturbed
Cooling

(-°C)	(% dry wt.)
0.33	11.42
0.48	10.12
0.64	8.21
0.80	7.71
0.88	7.31
1.24	6.80
1.40	6.10
1.50	6.30
2.18	5.60
2.89	5.59
4.12	4.98
4.86	4.48
6.17	4.17
7.05	3.67
9.22	3.46
11.41	2.96

Remolded
1st Warming

(-°C)	(% dry wt.)
10.61	2.41
5.41	3.25
1.34	6.61
1.08	7.13
0.95	7.76
0.69	9.96
0.61	15.84
0.46	21.92
0.38	33.36

Remolded
2nd Warming

(-°C)	(%dry wt.)
10.37	2.32
5.22	3.38
1.95	5.60
1.61	6.02
1.14	6.02
0.90	7.39
0.56	9.72
0.33	15.85
0.20	35.70

Remolded
3rd Warming

(-°C)	(% dry wt.)
10.29	2.43
5.14	3.17
0.90	8.13
0.46	10.46
0.28	23.35

Undisturbed Warming

(-°C)	(% dry wt.)
10.13	3.08
9.11	3.31
7.84	3.20
7.15	3.54
6.07	3.99
4.83	4.11
4.09	4.33
2.91	5.01
2.42	5.47
1.95	5.70
1.34	6.38
0.98	7.52
0.74	7.97
0.54	9.68
0.48	11.50
0.38	13.09
0.35	16.62
0.25	19.13

Undisturbed Cooling

(-°C)	(% dry wt.)
0.07	13.32
0.28	11.16
0.43	9.68
0.74	7.86
0.95	7.74
1.11	7.06
1.34	6.83
1.53	6.49
2.10	5.92
2.83	5.47
4.15	4.90
5.04	4.45
6.17	4.34
7.02	3.77
9.19	3.54
11.22	3.54

Remolded 1st Warming

(-°C)	(% dry wt.)
10.37	2.13
5.33	3.05
1.24	7.52
0.93	7.01
0.72	8.13
0.51	10.36
0.38	16.76
0.30	24.79
0.28	36.27

Remolded 2nd Warming

(-°C)	(% dry wt.)
10.37	1.95
5.22	2.67
1.97	4.83
1.68	5.45
1.19	5.76
0.90	6.79
0.67	8.84
0.22	16.05
0.20	35.28

Remolded 3rd Warming

(-°C)	(% dry wt.)
10.39	1.87
5.12	2.80
0.95	6.74
0.51	9.96
0.28	23.03

Specific gravity of soil:
2.710

Relative degree of saturation of undisturbed soil:
91.0%

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Undisturbed Warming

(-°C)	(% dry wt.)
10.37	1.19
9.25	0.71
7.95	0.71
7.23	1.19
6.15	0.95
4.93	1.42
4.22	0.71
3.04	0.95
2.44	1.42
2.10	1.66
1.45	2.13
1.06	2.13
0.85	2.84
0.61	3.08
0.48	3.79
0.43	4.27
0.35	5.92
0.25	7.35

Undisturbed Cooling

(-°C)	(% dry wt.)
0.07	3.79
0.38	3.32
0.59	2.61
0.90	2.37
1.11	2.61
1.19	1.66
1.45	1.42
1.58	1.90
2.13	1.42
2.83	1.42
4.20	0.71
5.09	0.71
6.17	0.95
7.05	0.71
9.27	0.71
11.19	0.71

Remolded 1st Warming

(-°C)	(% dry wt.)
10.15	1.08
5.22	1.08
1.03	2.97
0.85	2.43
0.69	2.70
0.43	4.04
0.35	7.82
0.25	14.29
0.22	24.80

Remolded 2nd Warming

(-°C)	(% dry wt.)
10.50	0.54
5.28	0.81
2.02	1.08
1.68	1.35
1.24	1.89
0.93	2.70
0.59	2.44
0.33	6.20
0.12	21.30

Remolded 3rd Warming

(-°C)	(% dry wt.)
10.45	0.75
5.22	0.50
0.98	1.76
0.54	3.26
0.28	11.54

Specific gravity of soil:
2.730

Relative degree of saturation of undisturbed soil:
81.9%

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Undisturbed Warming

(-°C)	(% dry wt.)
10.39	2.77
9.35	2.78
7.97	2.78
7.28	3.13
6.20	3.14
5.04	3.32
4.28	3.67
3.20	4.12
2.70	4.38
2.08	4.74
1.45	5.09
1.06	6.24
0.85	7.12
0.72	8.35
0.56	9.76
0.51	11.69
0.46	14.86
0.30	17.24

Undisturbed Cooling

(-°C)	(% dry wt.)
1.37	6.43
1.53	6.25
1.74	5.72
2.21	5.19
2.99	5.01
4.25	4.65
5.17	4.21
6.20	4.03
7.18	3.50
9.38	3.31
11.30	3.22

Remolded 1st Warming

(-°C)	(% dry wt.)
10.53	1.98
5.22	2.73
2.00	4.15
1.74	4.72
1.19	5.47
0.88	6.13
0.61	7.45
0.38	13.87
0.17	34.71

Remolded 2nd Warming

(-°C)	(% dry wt.)
10.53	1.98
5.22	2.73
2.00	4.15
1.74	4.72
1.19	5.47
0.88	6.13
0.61	7.45
0.38	13.87
0.17	34.71

Remolded 3rd Warming

(-°C)	(% dry wt.)
10.55	1.99
5.30	2.66
1.01	5.89
0.51	8.94
0.30	22.25

Specific gravity of soil:
2.650

Relative degree of saturation of undisturbed soil:
93.0%

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Undisturbed Warming

(-°C)	(% dry wt.)
10.50	1.33
9.59	1.21
8.21	1.22
7.34	1.72
6.33	1.60
5.20	1.86
4.22	1.74
3.10	2.13
2.60	2.26
2.08	3.27
1.45	2.78
1.03	3.42
0.69	4.18
0.69	5.20
0.48	6.60
0.46	8.12
0.38	10.92
0.30	13.46

Undisturbed Cooling

(-°C)	(% dry wt.)
0.35	10.29
0.51	7.11
0.77	5.45
1.03	4.56
1.16	3.92
1.32	3.41
1.61	3.03
1.89	3.28
2.44	2.77
3.07	2.51
4.20	2.24
5.22	2.11
6.31	2.22
7.28	1.72
9.43	1.46
11.43	1.45

Remolded 1st Warming

(-°C)	(% dry wt.)
10.23	1.27
5.01	2.08
1.06	4.16
0.77	5.09
0.59	5.78
0.33	7.74
0.25	14.91
0.25	24.97
0.04	42.77

Remolded 2nd Warming

(-°C)	(% dry wt.)
10.42	1.43
5.14	2.02
2.02	3.45
1.63	3.81
1.24	4.29
0.98	4.76
0.48	6.79
0.17	15.12
0.04	38.35

Remolded 3rd Warming

(-°C)	(% dry wt.)
10.37	0.96
5.17	1.67
0.82	4.77
0.51	8.24
0.17	23.64

Specific gravity of soil:
2.550

Relative degree of saturation of undisturbed soil:
98.9%

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Undisturbed Warming

(-°C)	(% dry wt.)
10.31	2.22
9.27	2.31
7.95	2.40
7.18	2.49
6.23	2.66
5.01	2.76
4.09	2.93
3.15	3.46
2.55	3.55
1.95	3.90
1.34	4.16
0.88	5.04
0.69	5.73
0.61	7.04
0.38	8.26
0.38	10.08
0.30	13.04
0.22	15.39

Undisturbed Cooling

(-°C)	(% dry wt.)
0.17	12.00
0.35	9.39
0.61	6.95
0.90	5.73
0.90	5.38
1.19	4.77
1.55	4.77
1.71	4.42
2.26	4.24
2.97	3.89
4.07	3.45
5.01	3.27
6.15	3.18
7.05	2.58
9.33	2.56
11.22	2.47

Remolded 1st Warming

(-°C)	(% dry wt.)
10.29	1.70
5.38	2.30
1.24	5.19
1.06	5.19
0.82	6.22
0.54	8.26
0.41	13.45
0.41	20.01
0.34	29.80

Remolded 2nd Warming

(-°C)	(% dry wt.)
10.71	1.55
5.36	2.33
2.15	3.54
1.79	3.88
1.27	4.23
1.03	5.18
0.64	6.38
0.38	12.08
0.20	26.92

Remolded 3rd Warming

(-°C)	(% dry wt.)
10.50	1.55
5.33	2.07
0.93	5.00
0.56	7.51
0.30	18.38

Specific gravity of soil:
2.680

Relative degree of saturation of undisturbed soil:
87.3%

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802/13/3

Undisturbed Warming

(-°C)	(% dry wt.)
10.50	1.86
9.51	1.80
8.26	1.92
7.36	1.92
6.31	2.03
5.20	2.09
4.17	2.26
3.15	2.43
2.55	2.54
1.97	2.71
1.45	2.88
0.95	3.17
0.72	3.45
0.54	4.02
0.43	4.87
0.35	5.61
0.25	7.25
0.17	9.12

Undisturbed Cooling

(-°C)	(% dry wt.)
0.35	5.10
0.54	4.53
0.80	4.08
1.03	3.73
1.21	3.51
1.37	3.51
1.66	3.28
1.79	3.17
2.39	3.05
3.10	2.83
4.22	2.54
5.22	2.43
6.31	2.43
7.28	2.14
9.38	2.03
11.54	1.97

Remolded 1st Warming

(-°C)	(% dry wt.)
10.37	1.55
5.09	1.98
1.14	3.26
0.82	3.69
0.72	4.49
0.41	5.08
0.25	8.50
0.25	15.34
0.15	26.83

Remolded 2nd Warming

(-°C)	(% dry wt.)
10.69	1.68
5.46	1.95
2.28	2.71
1.79	2.87
1.40	3.14
1.06	3.68
0.59	4.28
0.22	8.40
0.12	23.58

Remolded 3rd Warming

(-°C)	(% dry wt.)
10.53	1.70
5.22	1.86
0.88	3.34
0.43	5.20
0.09	14.30

Specific gravity of soil:
2.740

Relative degree of saturation of undisturbed soil:
96.2%

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802/18/4

Undisturbed Warming

(-°C)	(% dry wt.)
10.53	1.70
9.51	1.53
8.24	1.70
7.34	1.96
6.31	1.88
5.20	2.23
4.25	2.15
3.23	2.49
2.62	2.93
2.05	3.02
1.42	3.28
1.01	3.54
0.74	3.80
0.61	4.49
0.46	5.45
0.35	6.83
0.30	9.17
0.20	11.59

Undisturbed Cooling

(-°C)	(% dry wt.)
0.33	9.77
0.48	7.87
0.72	6.74
0.98	5.70
1.06	6.05
1.34	5.44
1.61	5.26
1.87	4.74
2.34	4.57
3.07	4.22
4.33	3.69
5.20	3.51
6.38	3.16
7.34	2.82
9.43	2.64
11.65	2.46

Remolded 1st Warming

(-°C)	(% dry wt.)
10.34	1.35
5.20	1.91
1.24	3.82
0.93	4.38
0.74	4.70
0.46	5.98
0.38	10.76
0.25	20.63
0.15	41.99

Remolded 2nd Warming

(-°C)	(% dry wt.)
11.33	1.59
6.01	2.25
2.68	3.26
2.42	3.76
2.02	4.18
1.61	4.93
0.59	6.26
0.28	14.20
0.20	38.84

Remolded 3rd Warming

(-°C)	(% dry wt.)
10.50	1.45
5.25	2.18
0.88	4.91
0.46	7.09
0.28	24.53

Specific gravity of soil:
2.710

Relative degree of saturation of undisturbed soil:
93.8%

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852802/4/2

Undisturbed Warming

(-°C)	(% dry wt.)
10.42	2.01
9.43	2.13
7.97	2.14
7.26	2.39
6.20	2.39
5.09	2.77
4.28	2.65
3.12	3.15
2.60	3.53
2.05	3.66
1.45	4.17
0.88	4.93
0.69	5.43
0.59	6.44
0.38	8.22
0.41	10.24
0.28	13.53
0.25	16.31

Undisturbed Cooling

(-°C)	(% dry wt.)
0.17	9.35
0.48	6.82
0.69	5.56
1.01	4.80
0.90	4.67
1.21	4.42
1.63	3.91
1.71	4.17
2.18	3.53
3.02	3.15
4.17	2.90
5.20	2.90
6.12	2.64
7.15	2.51
9.43	2.13
11.27	2.13

Remolded 1st Warming

(-°C)	(% dry wt.)
10.58	1.82
5.36	2.54
1.50	4.36
1.06	4.48
0.82	5.57
0.54	7.03
0.51	11.63
0.33	18.91
0.22	29.08

Remolded 2nd Warming

(-°C)	(% dry wt.)
11.25	1.35
5.83	2.21
2.60	3.07
2.18	3.32
1.61	3.81
1.50	4.18
0.59	6.03
0.28	14.14
0.17	35.42

Remolded 3rd Warming

(-°C)	(% dry wt.)
10.55	1.59
5.25	1.71
1.01	4.52
0.59	7.70
0.28	19.93

Specific gravity of soil:
2.680

Relative degree of saturation of undisturbed soil:
94.2%

Undisturbed Warming

(-°C)	(% dry wt.)
10.34	1.85
9.46	2.12
7.95	2.13
7.20	2.66
6.15	2.67
5.14	2.67
4.28	2.94
3.20	3.75
2.60	4.03
2.08	4.30
1.32	4.84
1.01	5.92
0.88	6.73
0.72	7.81
0.48	9.43
0.51	11.32
0.48	14.28
0.38	16.98

Undisturbed Cooling

(-°C)	(% dry wt.)
0.2	17.79
0.38	13.74
0.56	8.62
0.98	5.38
1.19	5.38
1.24	5.38
1.58	4.57
1.76	4.03
2.23	3.76
3.02	4.29
4.33	2.68
5.14	2.4
6.17	2.67
7.23	2.13
9.41	1.59
11.27	1.851

Specific gravity of soil:
2.680

Relative degree of saturation of undisturbed soil:
88.3%

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852802/6/1

Undisturbed Warming

(-°C)	(% dry wt.)
10.39	1.00
9.41	1.00
7.92	1.25
7.20	1.25
6.15	1.25
5.04	1.76
4.28	1.26
3.25	1.51
2.68	2.27
2.10	2.52
1.53	2.53
1.08	2.78
0.90	3.03
0.67	4.05
0.54	4.30
0.48	5.57
0.46	8.10
0.33	10.12

Undisturbed Cooling

(-°C)	(% dry wt.)
0.15	5.82
0.25	4.81
0.54	3.29
0.90	3.29
1.06	4.05
1.21	2.53
1.55	2.02
1.66	2.53
2.21	1.51
2.91	1.51
4.25	1.01
5.14	1.26
6.20	1.51
7.28	0.75
9.41	0.25
11.17	1.00

Remolded 1st Warming

(-°C)	(% dry wt.)
10.13	1.07
5.09	1.87
1.11	3.46
1.03	3.20
0.77	4.00
0.48	5.33
0.43	9.86
0.22	18.13
0.04	29.59

Remolded 2nd Warming

(-°C)	(% dry wt.)
10.55	0.56
5.33	0.83
2.08	1.39
1.71	1.95
1.29	1.95
0.98	2.78
0.64	3.62
0.35	7.51
0.20	24.49

Remolded 3rd Warming

(-°C)	(% dry wt.)
10.63	0.55
5.38	0.27
1.06	3.56
0.69	4.10
0.33	13.67

Specific gravity of soil:
2.820

Relative degree of saturation of undisturbed soil:
86.7%

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941201/1

Undisturbed Warming (-°C)	(% dry wt.)	Undisturbed Cooling (-°C)	(% dry wt.)	Remolded 1st Warming (-°C)	(% dry wt.)
10.37	2.55	0.17	10.65	10.05	1.73
9.35	2.70	0.33	7.91	5.04	2.36
7.89	2.71	0.61	6.23	1.03	5.36
7.18	3.01	0.95	5.62	0.82	5.67
6.12	2.87	1.06	5.47	0.61	7.09
4.99	3.32	1.19	5.01	0.38	10.25
4.33	3.63	1.55	5.31	0.33	17.34
3.12	3.79	1.58	4.71	0.22	25.54
2.57	4.09	2.26	4.55	0.07	37.52
2.08	4.40	2.91	3.94		
1.45	4.71	4.25	3.78		
1.14	5.32	5.07	3.48		
0.88	5.93	6.15	3.47		
0.54	6.84	7.12	3.16		
0.48	8.52	9.38	2.85		
0.51	10.04	11.25	2.70		
0.41	12.17				
0.33	15.21				

Remolded 2nd Warming (-°C)	(% dry wt.)	Remolded 3rd Warming (-°C)	(% dry wt.)
10.55	1.62	10.69	1.62
5.28	2.43	5.33	1.94
2.00	3.57	1.01	5.02
1.74	4.05	0.56	8.43
1.29	4.38	0.33	21.72
0.95	5.19		
0.59	7.29		
0.48	14.26		
0.15	34.20		

Specific gravity of soil:
2.700

Relative degree of saturation of undisturbed soil:
89.5%

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941201/2

Undisturbed Warming (-°C)	(% dry wt.)	Undisturbed Cooling (-°C)	(% dry wc.)	Remolded 1st Warming (-°C)	(% dry wt.)
10.26	1.58	0.15	19.27	10.02	1.72
9.27	1.71	0.33	13.13	4.96	2.58
7.92	1.47	0.61	9.42	0.90	5.91
7.23	1.85	0.88	8.01	0.77	6.15
6.12	1.98	1.19	7.24	0.56	7.26
4.93	2.37	1.14	6.60	0.28	9.97
4.22	2.63	1.45	6.34	0.20	19.32
3.12	3.02	1.63	6.59	0.12	33.10
2.62	3.28	2.26	5.56	0.02	50.32
2.05	3.54	2.86	5.04		
1.48	4.06	4.22	4.13		
1.06	4.70	5.12	3.86		
0.82	5.34	6.04	3.35		
0.54	6.62	7.05	3.33		
0.41	7.77	9.35	2.81		
0.43	9.43	11.14	2.54		
0.33	11.73				
0.20	14.03				

Remolded 2nd Warming (-°C)	(% dry wt.)	Remolded 3rd Warming (-°C)	(% dry wt.)
10.50	1.73	10.61	1.88
5.22	2.93	5.20	2.41
2.05	5.06	0.93	6.30
1.66	4.92	0.54	10.33
1.24	6.12	0.25	28.03
0.93	6.52		
0.56	8.12		
0.30	15.98		
0.22	42.20		

Specific gravity of soil:
2.640

Relative degree of saturation of undisturbed soil:
91.2%

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Undisturbed Warming (-°C)	(% dry wt.)
10.39	2.17
9.38	2.43
8.16	2.16
7.31	2.67
6.12	2.70
5.14	2.84
4.09	2.84
3.02	3.37
2.55	3.51
1.87	3.91
1.37	4.18
0.90	4.99
0.64	5.26
0.48	6.07
0.30	7.82
0.25	9.44
0.15	12.54
0.12	15.51

Undisturbed Cooling (-°C)	(% dry wt.)
1.32	5.40
1.63	5.13
1.79	4.86
2.36	4.59
2.99	4.05
4.22	3.65
5.20	3.65
6.31	3.78
7.26	2.84
9.30	3.11
11.49	2.71

Remolded 1st Warming (-°C)	(% dry wt.)
10.31	2.00
5.12	2.47
1.14	4.70
0.85	5.29
0.61	5.99
0.38	8.11
0.41	13.51
0.30	20.80
0.04	33.13

Remolded 2nd Warming (-°C)	(% dry wt.)
10.42	1.80
5.22	2.64
2.13	3.83
1.66	4.19
1.40	4.67
1.03	5.15
0.61	7.07
0.28	14.98
0.09	37.75

Remolded 3rd Warming (-°C)	(% dry wt.)
10.55	2.18
5.25	2.42
0.85	5.57
0.46	8.59
0.22	22.88

Specific gravity of soil:
2.720

Relative degree of saturation of undisturbed soil:
no data

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Undisturbed Warming (-°C)	(% dry wt.)
10.42	2.20
9.43	2.33
8.26	2.22
7.36	2.60
6.28	2.61
5.22	3.00
4.09	3.26
3.12	3.90
2.57	4.42
1.97	4.94
1.45	5.45
0.98	6.74
0.74	7.89
0.59	9.29
0.51	10.95
0.41	13.38
0.25	16.83
0.28	20.41

Undisturbed Cooling (-°C)	(% dry wt.)
0.3	18.74
0.61	13.5
0.77	10.05
1.06	8.77
1.21	7.36
1.29	7.11
1.63	6.84
1.76	6.33
2.39	5.56
3.02	5.17
4.22	4.51
5.22	4.12
6.33	3.6
7.26	3.34
9.43	3.07
11.46	2.43

Specific gravity of soil:
2.630

Relative degree of saturation of undisturbed soil:
93.4%

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Undisturbed Warming

(-°C)	(% dry wt.)
10.39	3.12
9.41	3.39
8.32	3.40
7.28	3.80
6.23	4.07
5.14	4.21
4.09	4.35
3.04	4.90
2.60	5.17
1.89	5.57
1.42	6.24
0.93	6.65
0.69	7.45
0.61	8.65
0.51	9.85
0.48	11.72
0.35	14.12
0.33	16.65

Undisturbed Cooling

(-°C)	(% dry wt.)
0.22	11.46
0.51	8.92
0.67	7.45
1.03	6.52
1.19	6.51
1.27	5.98
1.66	5.58
1.79	5.84
2.39	5.57
3.04	5.03
4.15	4.75
5.12	4.34
6.33	3.94
7.26	3.53
9.35	3.51
11.54	3.11

Remolded 1st Warming

(-°C)	(% dry wt.)
10.21	2.18
5.07	2.16
1.08	6.55
0.64	6.43
0.54	7.65
0.22	18.93
0.04	29.86

Remolded 2nd Warming

(-°C)	(% dry wt.)
10.37	1.97
5.14	2.71
2.00	4.44
1.55	4.69
1.14	5.55
0.74	6.41
0.56	7.89
0.22	16.53
0.15	39.83

Remolded 3rd Warming

(-°C)	(% dry wt.)
10.42	2.11
5.20	2.73
0.85	6.09
0.43	9.20
0.17	24.12

Specific gravity of soil:
2.660

Relative degree of saturation of undisturbed soil:
91.3%

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Tice, Allen R.

Unfrozen water contents of undisturbed and remolded Alaskan silt as determined by nuclear magnetic resonance / by Allen R. Tice, Patrick B. Black and Richard L. Berg. Hanover, N.H.: U.S. Army Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1988.

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